

NAS Pensacola, FL

Optimization of Remedial Action Operation to Treat Chlorinated Hydrocarbons in Groundwater

Summary

The Navy, in conjunction with regulators, optimized remedial action operations (RAO) at a former sludge drying bed and surge pond site at Naval Air Station (NAS) Pensacola, Florida. The RAO optimization implemented over the past several years has resulted in improvements in the monitoring program, a modification in remedial strategy, accelerated site cleanup, and significant cost savings.

The monitoring program improvements reduced the sampling frequency and the number of constituents being analyzed. Additionally, the number of monitoring wells was reduced from 19 to 15, and the contract type was changed from a cost plus to a fixed price contract. These actions have saved the Navy over \$200,000 in annual monitoring costs.

Modifications to the remedial strategy have progressed from optimizing the existing pump-and-treat (P&T) remedy, including reducing the number of recovery wells from seven to three, to redirecting the project to a passive final remedy, monitored natural attenuation (MNA). The remedy was redirected by assessing the natural attenuation capacity of the aquifer and implementing an aggressive source reduction technology, in-situ chemical oxidation, to reduce the relatively high concentrations of trichloroethene (TCE) and other chlorinated volatile organic compounds (CVOCs).

The in-situ chemical oxidation treatment substantially reduced contaminant concentrations in the source area and ensured natural attenuation processes would remediate remaining downgradient contamination in a reasonable timeframe and protect the closest receptor, Pensacola Bay. As a result, the regulatory agency has allowed the P&T system to be permanently discontinued, and the corrective action plan (CAP) and Resource Conservation and

Recovery Act (RCRA) permit are being modified to specify MNA as the final remedy. Engineering this more cost-effective remedy has saved the Navy approximately \$2,000,000 in remedial action costs.

1.0 Site Background

1.1 Site Description

NAS Pensacola occupies approximately 5,800 acres on a peninsula in southern Escambia County, 5 miles south of the city of Pensacola, Florida. The former sludge drying beds and surge pond were located on a peninsula on the northeast side of the NAS. These units are associated with the former industrial wastewater treatment plant (IWTP), now a domestic wastewater treatment plant (WWTP), that received wastewater from activities on NAS property, including aircraft maintenance and metal plating.

Materials treated in the IWTP, such as degreasers and paint strippers, were leaked from various sources at NAS Pensacola, resulting in discharge of chlorinated solvents into the sludge drying beds and surge pond. Chlorinated solvents and other compounds that accumulated in the sludge drying beds and surge pond subsequently leaked to the underlying soil and groundwater.

In July 1986, the Environmental Protection Agency (EPA) conducted an inspection of the IWTP for compliance with RCRA. The EPA determined that operation of the IWTP was not in compliance with regulatory and statutory requirements of RCRA and issued a Notice of Violation (NOV). The NOV resulted in closure of the unlined sludge drying beds in 1987 and the surge pond in 1988, on the basis that they had been receiving listed wastes (spent solvents) from the IWTP.

As part of the RCRA closure, the sludge drying beds and surge pond were excavated, backfilled and

capped. A groundwater extraction system was installed in 1987 to recover contaminated groundwater and to prevent migration of the contaminant plume to Pensacola Bay. The operation of this P&T system and monitoring of groundwater are requirements of the RCRA permit.

NAS Pensacola was placed on the National Priorities List (NPL) in December 1989, and a Federal Facilities Agreement (FFA) was signed in October 1990. A Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) remedial investigation and feasibility study (RI/FS) of the WWTP area was completed in 1995 and the resulting record of decision (ROD) specified that contaminated groundwater would continue to be addressed under the RCRA permit.

1.2 Site Geology and Hydrogeology

Subsurface geology at the site consists primarily of relatively homogeneous fine to medium grained sand. A gray clay layer was encountered between 40 and 60 feet below ground level (ft bgl) during installation of the intermediate (36 to 48 ft bgl) and deep (65 to 70 ft bgl) monitoring wells. Shallow groundwater monitoring wells (10 to 20 ft bgl) are all completed in fine to medium grained sand.

The aquifer underlying the site is divided into three zones, corresponding with the three depths of monitoring wells. These zones exhibit varying hydraulic gradients and conductivities, as well as flow directions and rates. Overall, site groundwater flow is toward Pensacola Bay, which borders the site to the east. The depth to groundwater is generally less than 5 ft bgl at the site.

2.0 Monitoring Program

2.1 Initial Monitoring Program

Site contaminants consist primarily of volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and metals resulting from the handling of hazardous materials at NAS Pensacola. Assessment monitoring of groundwater has been performed at the site since 1987. In January 1992,

the monitoring frequency was reduced from quarterly to semiannually. Reporting of the monitoring results is also performed on a semiannual basis.

The initial groundwater monitoring program included 19 monitoring wells, which were sampled quarterly and analyzed for 119 parameters. The groundwater monitoring network for the site included a background well, eight “point of compliance” (POC) wells, and ten assessment wells.

2.2 Monitoring Program Improvements

In the spring of 1996, the Navy began reviewing site history and data to identify an alternative to a groundwater remediation and monitoring approach that was considered excessive and not cost effective. As detailed in *Ground Water Monitoring Optimization Case Study, NAS Pensacola, FL, Sludge Drying Beds/Surge Pond Ground Water Monitoring*, the following actions were taken to reduce monitoring costs associated with this site:

- Change the contractor and contract type from cost plus to fixed price.
- Reduce the number of wells being monitored from 19 to 15.
- Eliminate the monitoring for analytes that have not been detected for three years.
- Shift some of the routine maintenance tasks for the P&T system away from contractor personnel to installation personnel.

Additionally, monitoring frequency had been reduced from quarterly to semi-annual in 1992. Table 1 shows the initial and current wells in the groundwater monitoring program. Figures 1 and 2 show the shallow and intermediate groundwater monitoring well network.

2.3 Monitoring Program Costs

The annual cost of the monitoring program in 1992 was \$302,370. In 1998, the annual cost was \$101,615, reflecting annual savings of over \$200,000 from monitoring improvements.

Table 1. Initial and Current Groundwater Monitoring Program

	Background	Point of Compliance	Assessment
Initial (19 wells total)	UG-1	PCS-1, PCI-1, PCD-1, GM-8, GM-9, GM-10, GM-68, GM-69	GM-62, GM-63, GM-64, GM-65, GM-66, GM-67, GM-11, GM-12R, GM-13, GM-14
Current (15 wells total)	UG-1	PCS-1, PCI-1, PCD-1, GM-8, GM-9, GM-10, GM-68, GM-69	GM-65, GM-66, GM-67, 33G12, 33G16, 33G20

3.0 Remedial Action Operation

3.1 Initial Operations

Following closure of the sludge drying beds and surge pond, waste was dewatered to a solid state, containerized, and disposed of as a listed waste. In 1989, the sludge beds and surge pond structures were removed and source area reduction action was conducted. The underlying contaminated soils were excavated to the water table, and backfilled with clay soil. The sludge drying bed area was capped with asphalt and the surge pond area was capped with clay.

To recover and treat contaminated groundwater and to prevent migration to Pensacola Bay, a groundwater extraction system with seven recovery wells was activated at the site in February 1987. In 1995, a comprehensive data review, including spatial and time-series trend analysis of monitoring well data, indicated groundwater contamination had been reduced to levels near or below the specified groundwater protection standards, maximum contaminant levels (MCLs), across most of the site. However, relatively high concentrations of trichloroethene (TCE) averaging about 3,000 to 4,000 ug/L had persisted for several years in the intermediate depth monitoring well GM-66. Concentrations in monitoring wells were observed to decrease to below MCLs within 250 ft downgradient of GM-66, approximately 300 ft before reaching Pensacola Bay. Concentrations in shallow and deep monitoring wells were observed to be below or near MCLs indicating the remaining contamination existed primarily in the intermediate zone, approximately 35–40 ft bgl, just above the confining clay layer.

As a result of the analysis, the extraction system was optimized in 1995 by reducing the number of recovery wells from seven to three to focus recovery efforts in the area near monitoring well GM-66. Additionally, the analysis indicated that natural attenuation processes were helping to contain and remediate the plume and led to a more formal assessment of natural attenuation.

Extracted groundwater was originally treated at the IWTP when the recovery well system was installed in 1987. When the IWTP was converted to a domestic-waste-only treatment plant in October 1995, a tray-type air stripper was installed to pre-treat contaminated groundwater.

3.2. Natural Attenuation Assessment

In 1996, groundwater monitoring at the site was modified to include an ongoing assessment of the potential for natural attenuation to help remediate the site. Natural attenuation processes, such as dilution, adsorption and biodegradation, may contribute to the reduction of contaminants in the groundwater; however, the efficiency of these processes varies widely in different groundwater systems and for different chemical compounds. In the study, the efficiency of natural attenuation of chlorinated ethenes and benzenes in the groundwater system underlying the WWTP was evaluated.

The primary focus was to assess the natural attenuation of chlorinated ethenes, primarily TCE and its biodegradation products, in the vicinity of GM-66 along flowpath A-A'. The secondary focus was to assess the natural attenuation of chlorinated benzenes in less contaminated areas near GM-69

along flowpath B-B'. Figure 3 illustrates the flowpaths evaluated in the assessment.

The primary study in the area of higher concern concluded that TCE and its biodegradation products, cis-1,2 dichloroethene (DCE), vinyl chloride (VC) and 1,1 dichloroethane (DCA), along A-A' are subject to efficient natural attenuation under the anoxic groundwater conditions. The attenuation process reduces concentrations of these contaminants below detectable levels in groundwater prior to reaching Pensacola Bay.

For this primary study along A-A', one temporary well (USGS-5) was installed upgradient of GM-66 and three temporary wells (USGS-1, USGS-2, and USGS-6) were installed downgradient to monitor geochemical conditions and changes in concentrations of TCE and its biodegradation products. Monitoring data indicated that redox conditions (Figure 4) were favorable for natural attenuation of chlorinated ethenes; TCE and its biodegradation products (Figure 5) were completely destroyed within 250 feet downgradient of the source area, primarily as a result of sequential reductive dechlorination (Chapelle and Bradley, 1999).

Conversely, the secondary study along B-B' concluded that natural attenuation processes for chlorinated benzenes were not efficient in the anoxic groundwater system. However, the chlorinated benzene plume was observed to attenuate downgradient (Figure 6), primarily due to dilution in the aquifer as groundwater flows back and forth with tidal fluctuations. Biodegradation may also be contributing to the observed attenuation of the chlorobenzenes under the oxic groundwater conditions induced by the tidal action near the groundwater/surface water interface (Figure 7).

Diffusion sampler surveys in the surface water bed sediments showed no evidence that chlorinated benzenes are discharging to Pensacola Bay. Likewise, a new monitoring well installed in the

tidal influence zone indicated concentrations of chlorinated benzenes had been reduced to below MCLs (Chapelle and Bradley, 1999).

Based on the favorable quarterly data from the first year of the assessment, the Navy and the regulatory agency, Florida Department of Environmental Protection (FDEP), agreed to temporarily discontinue operation of the P&T system to further assess the efficiency of natural attenuation processes. Concurrently, source reduction technologies would be demonstrated in the source area near GM-66 to complement natural attenuation and accelerate remediation of the site.

3.3. In-Situ Chemical Oxidation for Source Reduction

In 1998, in-situ chemical oxidation for source reduction was implemented to accelerate remediation at the site and to enhance natural attenuation processes. The groundwater source area near GM-66 was further delineated and characterized with direct push sampling at 5-ft depth intervals. TCE and its biodegradation products were identified at maximum concentrations of 3,600 ug/L TCE, 520 ug/L DCE and 63 ug/L VC. The injection well locations and the interpreted plume area are shown in Figure 8.

Based on the site-specific contaminants of concern, the hydrogeologic parameters, and the localized area to be treated, in-situ chemical oxidation using the Fenton's Reagent method was selected as the technology for source reduction. The in-situ chemical oxidation process is intended to reduce organic contaminant concentrations in groundwater. The process is an aggressive, pressurized injection of concentrated hydrogen peroxide and ferrous iron catalyst used to treat localized areas of relatively high concentrations of organic contamination. The process uses Fenton's Chemistry to create hydroxyl radicals, which are powerful, effective, and nonspecific oxidizing agents, within the groundwater. The hydroxyl radicals react with

chlorinated compounds in the groundwater to form water, carbon dioxide, and hydrogen and chloride ions, which are all non-toxic at the levels produced.

The treatment program was initiated with injector installation in November 1998. Based upon the interpreted plume area, six carbon steel injectors were installed within the former sludge drying bed in a vertical array from 11 to 31 ft bgl and 8 injectors were installed at 35-40 ft bgl to target the area downgradient of the sludge drying bed. This installation also provided additional sampling points for source area delineation. The initial field injection program was conducted in December 1998; a second injection phase was conducted in May 1999. Results of the treatment program are summarized in Table 2.

During Phase I, a total of 4,089 gallons of 50% hydrogen peroxide and a similar volume of ferrous iron catalyst solution were injected over the course

of 5 days in December 1998. Groundwater samples were collected daily during the injection and 4 rounds were collected over a 4-month period following injection. Post-treatment samples indicated that an 81% reduction in total CVOCs from pre-treatment levels was achieved and maintained in GM-66 over the treatment period; however, USGS-5 and USGS-6 experienced rebound with post-treatment TCE concentrations slightly higher than pre-treatment levels.

To explain the lack of contaminant reductions in USGS-5 and USGS-6, additional soil and groundwater sampling was conducted. The possibilities examined were that undetected sorbed-phase or dissolved-phase contamination existed within, adjacent, or above the treatment area; that organic matter was present at unusually high levels and consumed the available hydroxyl radicals through oxidation; or that the aquifer geochemistry

Table 2. Effect of Treatment Program on TCE and Total VOCs Concentrations

Location Date/CVOC	GM-66 / 66R			USGS-5			USGS-6		
	TCE	CIS	VC	TCE	CIS	VC	TCE	CIS	VC
7/98	3,600	520	63	-	-	-	-	-	-
8/20/98	2,440	403	115	1,420	169	49	743	369	976
12/1/98	2,040	430	138	2,460	218	31	773	344	595
12/9/98	3,000	510	53	1,700	200	14	-	-	-
Samples collected during and after Phase I injection (Dec 7-12, 1998)									
12/10/98	180	16	<1	<1	<1	<1	-	-	-
12/11/98	200	31	2	830	103	6	-	-	-
12/12/98	130	10	<1	<1	<1	<1	-	-	-
12/29/98	485	42	<5	1,820	140	11	825	391	575
1/99	190	ND	ND	-	-	-	-	-	-
1/27/99	415	27	4	2,100	<5	6	926	<5	218
4/7/99	460	38	<1	2,700	210	17	890	380	250
Samples collected during and after Phase II injection (May 11-17, 1999)									
5/11/99	310	27	<1	1,600	180	7	500	280	180
5/12/99	<1	<1	<1	960	130	7	45	27	18
5/13/99	510	37	<1	1,900	170	11	81	46	38
5/14/99	330	33	2	<1	180	19	590	340	250
5/15/99	370	77	27	120	16	5	550	350	250
5/17/99	1	<1	<1	110	<1	<1	<1	<1	<1
5/20/99	<1	<1	<1	79	10	1	32	14	6
6/21/99	<5	<1	<1	100	20	3	110	49	21
7/15/99	86	8	<5	-	-	-	-	-	-
1/11/00	180	18	<5	-	-	-	-	-	-

affected the reaction kinetics of the Fenton's chemistry.

The sampling data did not indicate the presence of additional source area contaminants or other organic matter. However, geochemistry data indicated naturally occurring dissolved ferrous iron concentrations were found to be exceptionally high (up to 975 mg/L) within the treatment area prior to the Phase I injection. Because dissolved iron serves as a catalyst in the Fenton's reagent method, the naturally occurring elevated iron concentrations limited the radius of influence and decreased treatment effectiveness. Accordingly, the injection program was modified to include phosphoric acid to buffer and slow the Fenton's reaction and increase the effective radius of influence.

Post-treatment sampling also indicated that the screen in monitoring well GM-66 was damaged, so GM-66R was installed directly adjacent with identical construction. Modifications also included installing an additional injector, I-15, in the immediate sludge drying bed source area at a depth of 35-40 feet bgl. The second injection phase was then conducted in May 1999.

During Phase II, an additional 6,038 gallons of 50% hydrogen peroxide and a similar volume of catalyst was injected over a 6-day period. Groundwater was sampled daily during the treatment and again 30 days after treatment. Post-treatment samples indicated that CVOCs at GM-66R were reduced to below detection levels. Compared to Phase I pre-treatment levels, Phase II post-treatment samples at USGS-5 exhibited a 97% reduction in CVOCs from 2,709 ug/L to 90 ug/L, and USGS-6 exhibited a 97% reduction from 1,712 ug/L to 52 ug/L. Thirty days after treatment, CVOCs at GM-66R were still below detection levels. USGS-5 and USGS-6 had exhibited only slight rebound to 123 ug/L and 180 ug/L, respectively. Subsequent data collected during ongoing semi-annual RCRA monitoring indicates CVOCs at GM-66R rebounding slightly to 94 ug/L two months after treatment and to 198 ug/L (8% of

pre-treatment levels) eight months after treatment. Figure 9 details the analytical results of the treatment program.

Based on these results, the combined Phase I and Phase II injections successfully met the treatment goal of substantial source reduction. The reduction of source area concentrations ensures the protectiveness and timeliness of MNA as the final remedy.

3.4. Monitored Natural Attenuation - The Final, Polishing Remedy

In October 1999, results of the ongoing quarterly natural attenuation monitoring were summarized in a report to FDEP (Chapelle and Bradley, 1999). The purpose of the study was to further assess the potential for natural attenuation as part of the overall site remediation. The study concluded that the estimated natural attenuation capacity of the aquifer at this site is approximately 10% contaminant loss per foot of flowpath for chlorinated ethenes.

Based on results of the source area reduction and the observed natural attenuation rate of the system, the study estimates that it will take about three to five years for chlorinated ethenes in the residual plume to decline below MCLs, i.e., 5 ug/L for TCE. Also, the reduction of contaminant concentrations below MCLs indicates that additional remedial measures are not required to protect Pensacola Bay. The study indicates that monitored natural attenuation (MNA) is an effective remedial strategy for polishing residual contamination at this site. The source reduction project had enhanced MNA, making it a more timely remedy.

3.5. Modified Corrective Action Plan

Based on results of the chemical oxidation source reduction and the conclusions of the ongoing MNA study, the FDEP is allowing the P&T system to be permanently discontinued. The verification of contaminant reduction by natural attenuation must be documented by continued plume monitoring. A modified corrective action plan (CAP) and proposed

RCRA permit modification were submitted to FDEP in January 2000. The modifications include the permanent shutdown of the P&T system and the implementation of MNA as the final, polishing remedy for the site with a contingency plan for additional corrective action if warranted by any future migration of contaminants to established sentinel wells.

3.6 Remedial Action Costs

The implementation of the modified remedial strategy will result in significant time and cost savings. The original P&T remedial strategy would require at least 20 years to meet cleanup goals. With an annual operating and monitoring costs of \$70,000 and \$100,000 per year, respectively, the total cost of the P&T remedial strategy over 20 years would be \$3,400,000.

The costs of the modified remedial strategy include the implementation of in-situ treatment and conversion to MNA, and cost savings for the permanent discontinuation of the groundwater treatment system. The modified remedial strategy would require approximately three to five years to meet the cleanup goals. With treatment and annual monitoring costs of \$250,000 (total) and \$100,000 per year, respectively, the total cost of the modified remedial strategy over five years would be \$750,000.

A life-cycle cost savings of approximately \$2,650,000 would be realized with the conversion to MNA as the remedial strategy. The cost savings calculated as a net present value (assuming 6% interest and 3% inflation) is approximately \$1,800,000.

4.0 Conclusions

For the site-specific conditions at the WWTP area at NAS Pensacola, in-situ chemical oxidation using the Fenton's Reagent method has proven to be a successful and economical technology for aggressively reducing groundwater source area concentrations of CVOCs. Coupled with analyses of

the natural attenuation capacity, the substantial source reduction has 1) ensured the protection of the downgradient receptor, Pensacola Bay, 2) ensured the effectiveness and timeliness of MNA as the final, polishing remedy, 3) eliminated the need for the existing P&T system, and 4) substantially reduced long-term remedial action operation and monitoring costs.

5.0 Lessons Learned

5.1 Regulator Interface

State regulatory interface has been a critical element for optimizing the monitoring program and remedial actions at NAS Pensacola. When the RCRA permit was due for renewal in 1996, Southern Division technical personnel proposed an enhanced groundwater management strategy based on an analysis of historical groundwater data that indicated contamination was attenuating naturally. The combination of monitored natural attenuation and source reduction was proposed to be evaluated as a remedial alternative to the existing P&T system. The Navy requested a one-year shutdown of the groundwater treatment system to further verify the effectiveness of natural attenuation and to perform source reduction with in-situ chemical oxidation. Additionally, as part of the revised permit negotiations in 1996, the number of monitoring wells was reduced and constituents that had not been detected for three years were eliminated from the monitoring analyte list.

5.2 Site-Specific Advantages and Limitations

Site-specific advantages and limitations of any treatment technology should be evaluated as part of the feasibility study. Aquifer characteristics that may affect treatment using the Fenton's Reagent method of in-situ chemical oxidation are known to include physical properties such as hydraulic conductivity and heterogeneity, and geochemical properties, including pH, alkalinity, organic content, and concentration of dissolved ferrous iron.

At the NAS Pensacola site, the relatively homogeneous sands in the targeted source area provided sufficient permeability to allow effective distribution of the injected Fenton's Reagent. Likewise, the low pH of 2 to 3 and relatively low alkalinity were conducive to the effectiveness of the technology. However, results from the Phase I injection indicated treatment effectiveness and the radius of influence was limited. Factors that may have limited the radius of influence were investigated including:

- The presence of native or anthropogenic organic matter in the soil and groundwater that may react with hydroxyl radicals, thus reducing overall efficiency.
- The aquifer geochemistry, which may affect the reaction kinetics and treatment effectiveness of the Fenton's chemistry.

Groundwater samples indicated that naturally occurring dissolved iron levels were exceptionally high, ranging from 475 to 975 mg/L. Because ferrous iron acts as a catalyst in the Fenton's reaction, the high concentrations that were naturally occurring in the aquifer resulted in rapid hydrogen peroxide decomposition. The rapid decomposition reduced the hydrogen peroxide efficiency, reduced the radius of influence, and limited the effectiveness of the treatment. To address the problem and increase the radius of influence and effectiveness of Phase II treatment, dilute phosphoric acid was also injected with the hydrogen peroxide to form complexes with the dissolved iron and to stabilize and slow the Fenton's reaction.

Such site-specific factors should typically be evaluated as part of the feasibility study and design process when considering in-situ chemical oxidation, as well as other technologies. If adequate soil and groundwater data are not available, then additional field data should be collected prior to implementing the technology.

5.3 Secondary Effects of Chemical Oxidation

Secondary effects should be evaluated when implementing in-situ chemical oxidation treatment. The Fenton's Reagent chemical oxidation reaction is an exothermic reaction, which generates heat and pressure. The heat and pressure may cause mounding in the subsurface and result in mobilization of contaminant into or from the unsaturated area and peripheral areas of the treatment zone. To properly assess potential secondary effects of chemical oxidation, good site characterization is needed.

An anomaly at the NAS Pensacola site that may be a secondary effect of the in-situ chemical oxidation was observed. During a semi-annual RCRA monitoring event that followed the Phase I injection, a significant spike in chlorobenzene and benzene concentrations was observed in a shallow monitoring well upgradient of the treatment area and adjacent to the asphalt-capped, former sludge drying bed area. Based on the relative proximity to the injection area, groundwater mounding from the injection and exothermic reaction may have mobilized localized contaminants from the vicinity of the former sludge drying bed area. Alternatively, the concentration spike may coincidentally reflect a natural pulse of contaminants from groundwater beneath the capped area. Subsequent monitoring results indicate that the concentrations are still elevated, but have declined since the spike occurred.

6.0 References

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Maughon, M. J., C.C Casey, J.D. Bryant, and J.T. Wilson, 2000, “Chemical Oxidation Source Reduction and Natural Attenuation for Remediation of Chlorinated Hydrocarbons in Groundwater.”

7.0 Contact Information

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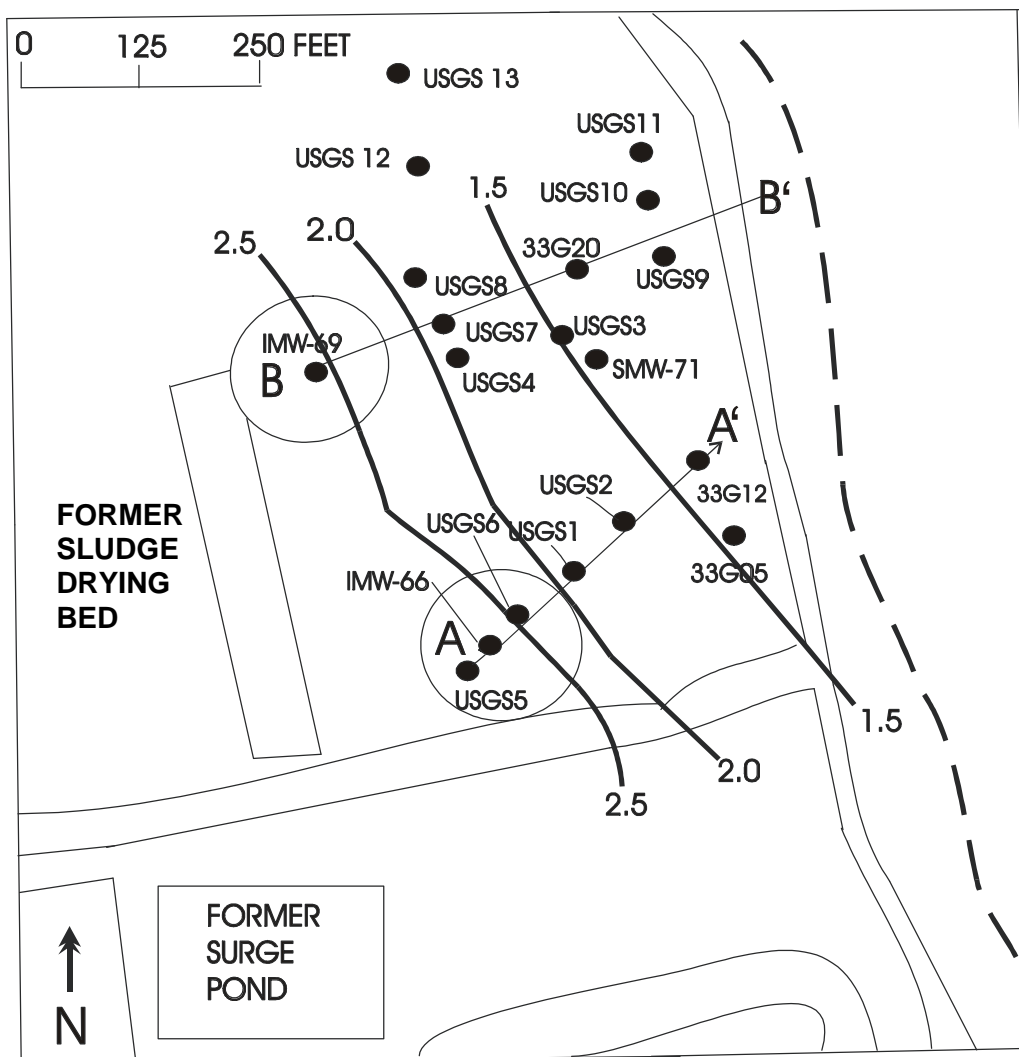


Figure 3. Location of monitoring wells, contours of intermediate zone water levels, and orientation of groundwater flowpaths A-A' and B-B'.

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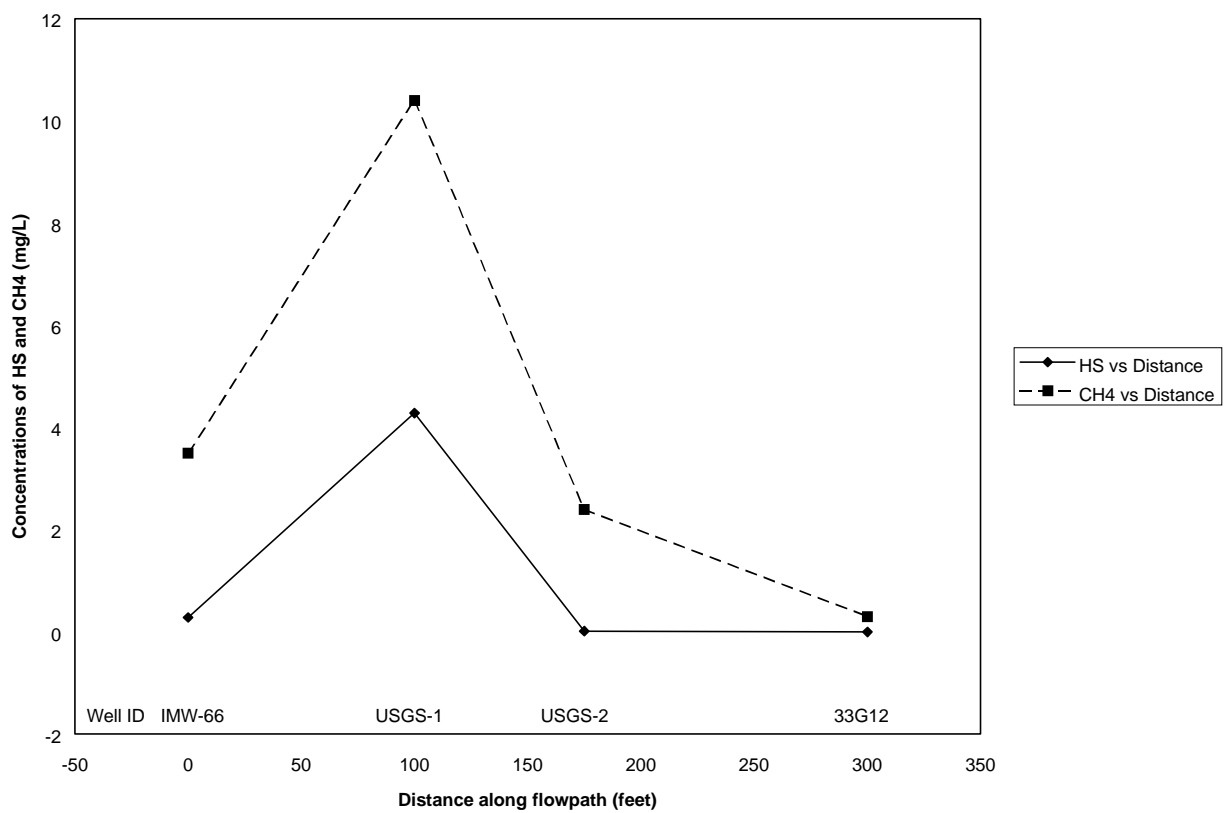
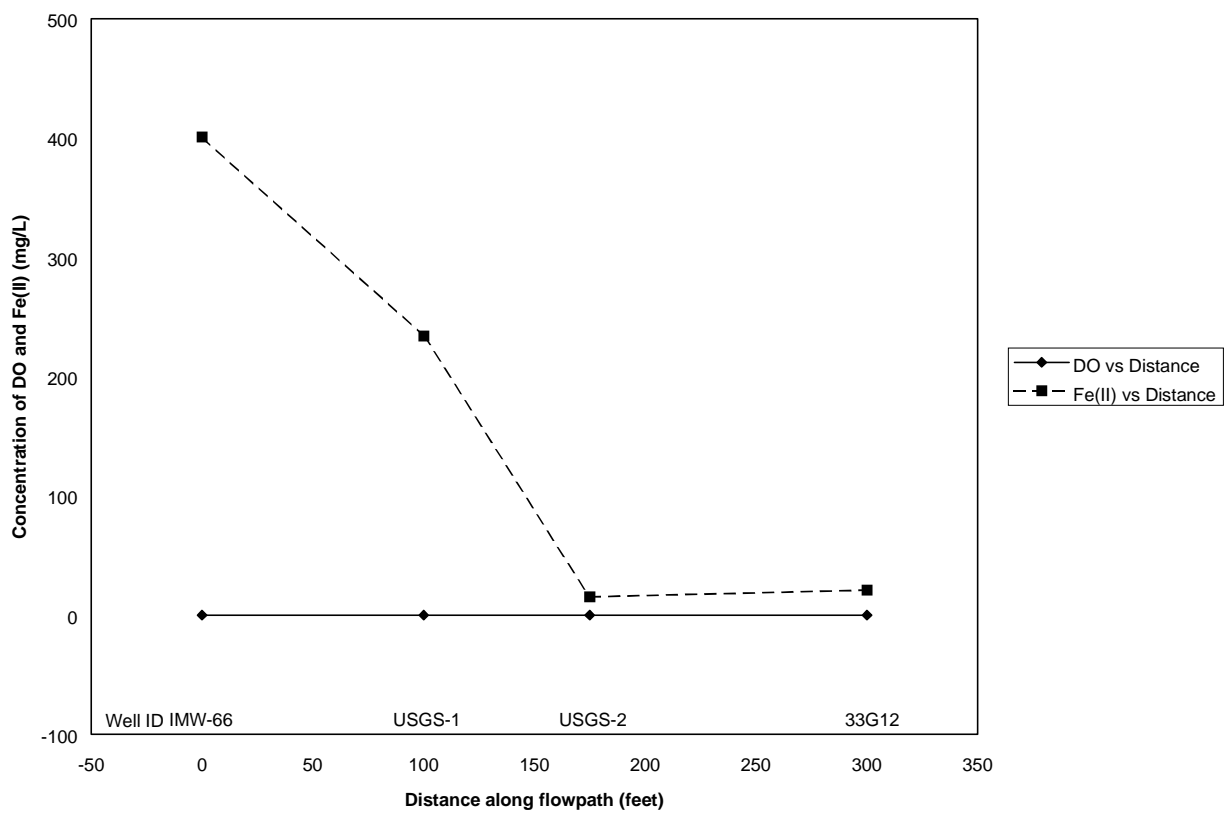


Figure 4. Concentrations of redox indicators along flowpath A-A', 3/24/97

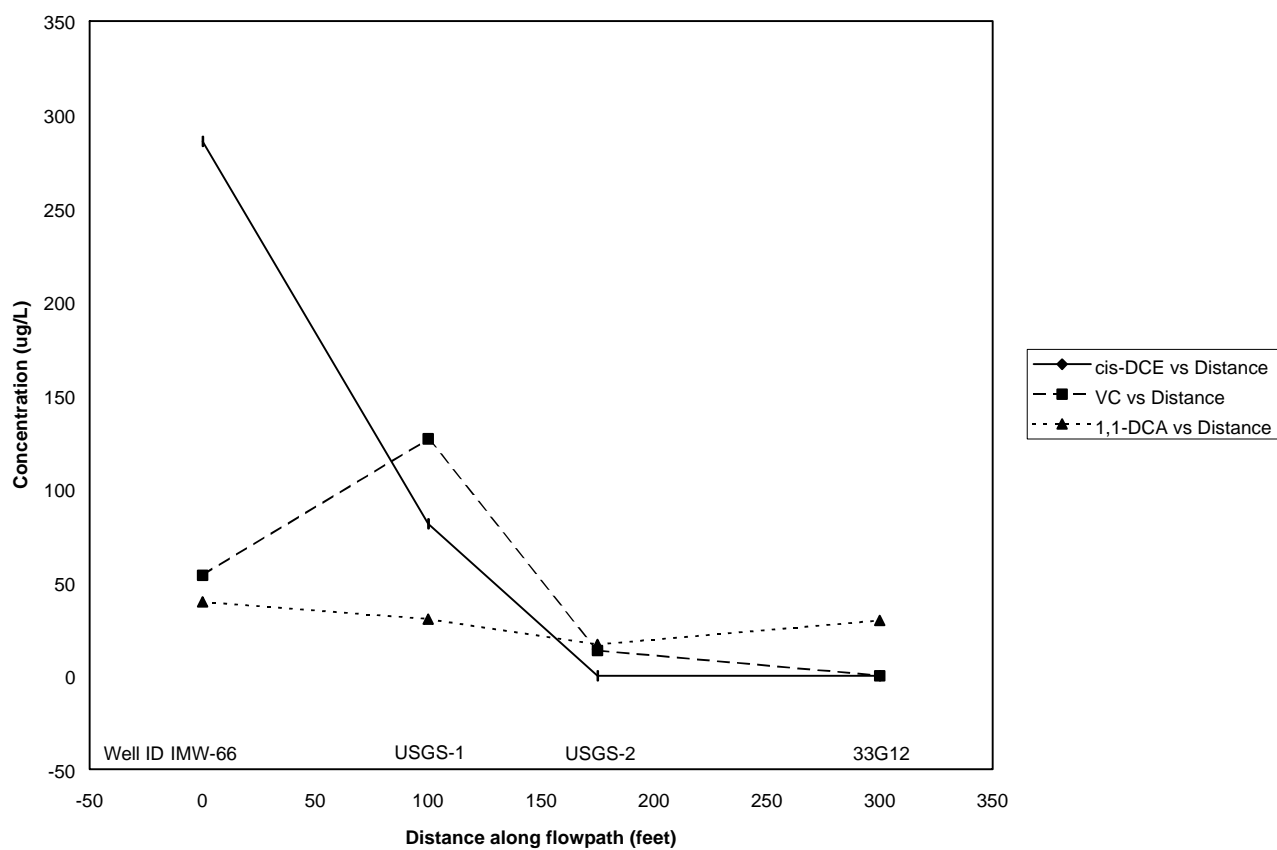
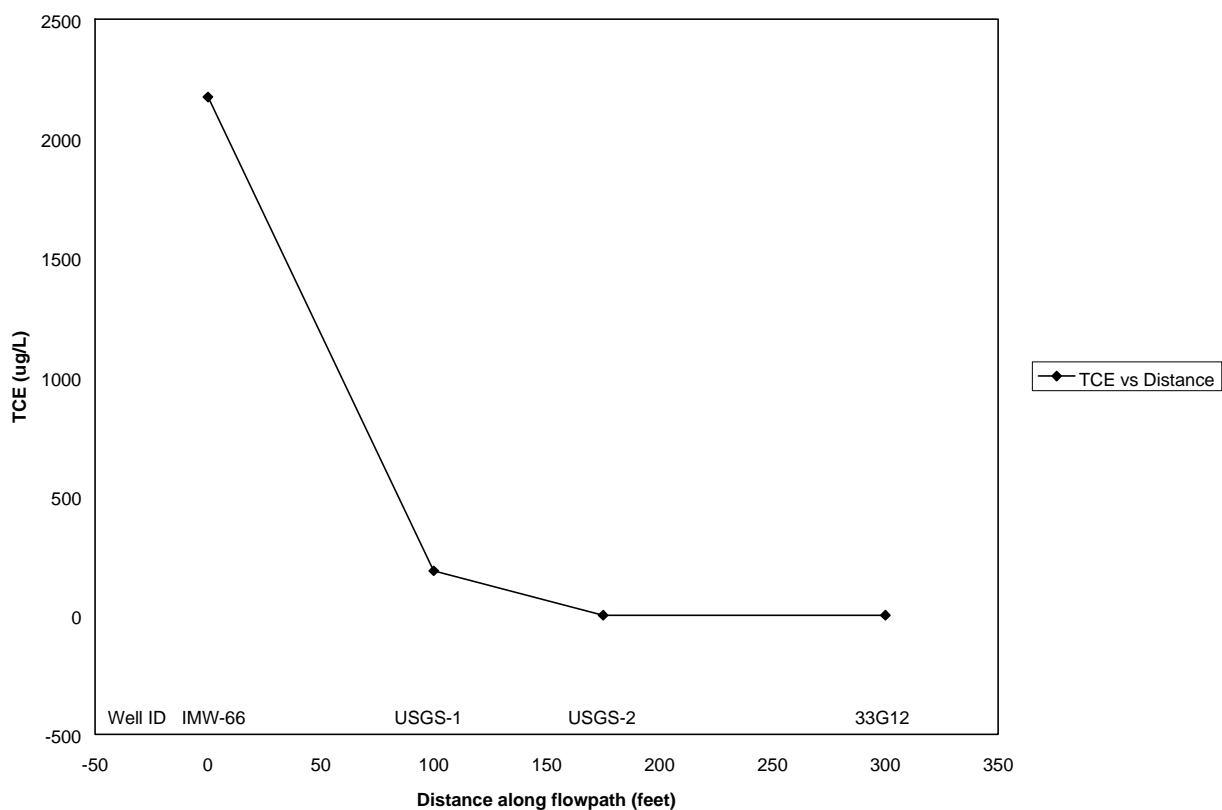


Figure 5. Concentrations of TCE and biodegradation products along flowpath A-A', 3/24/97

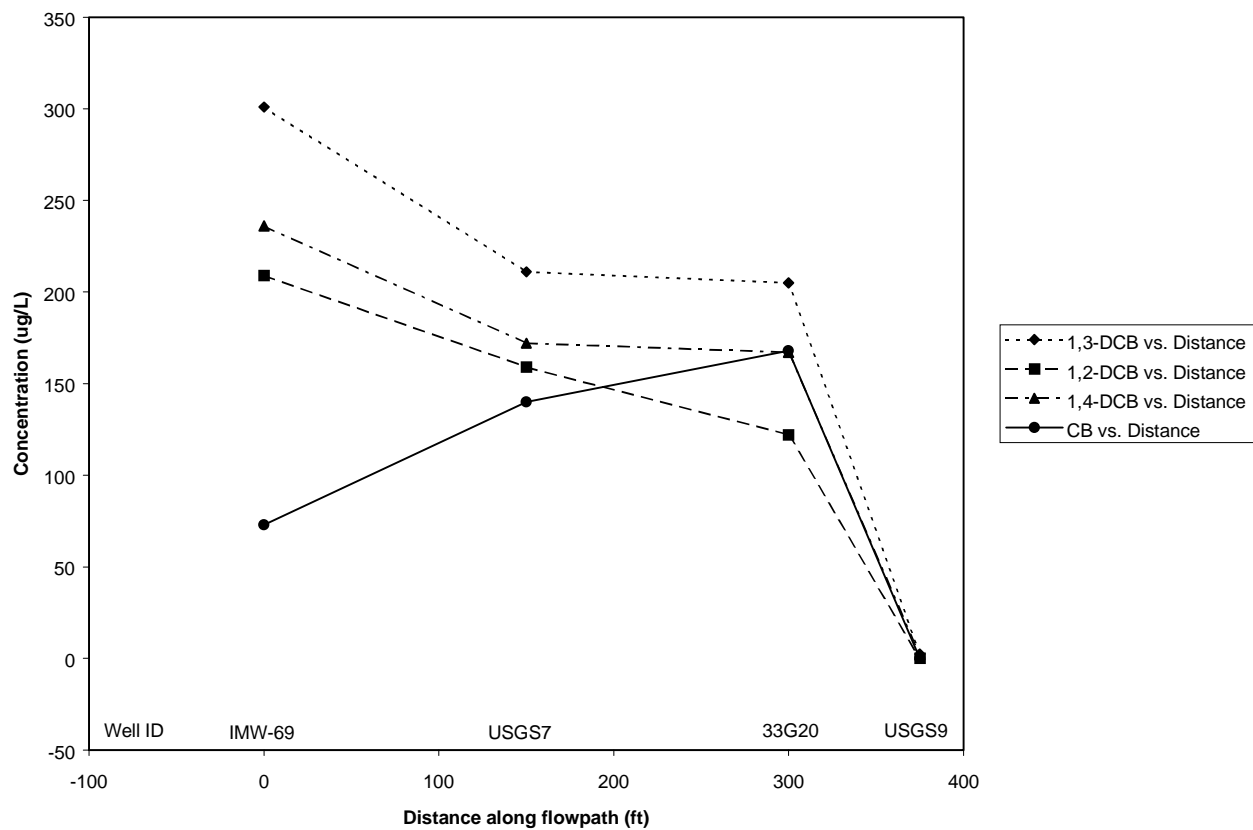


Figure 6. Concentrations of chlorobenzenes along flowpath B-B', 4/7/99

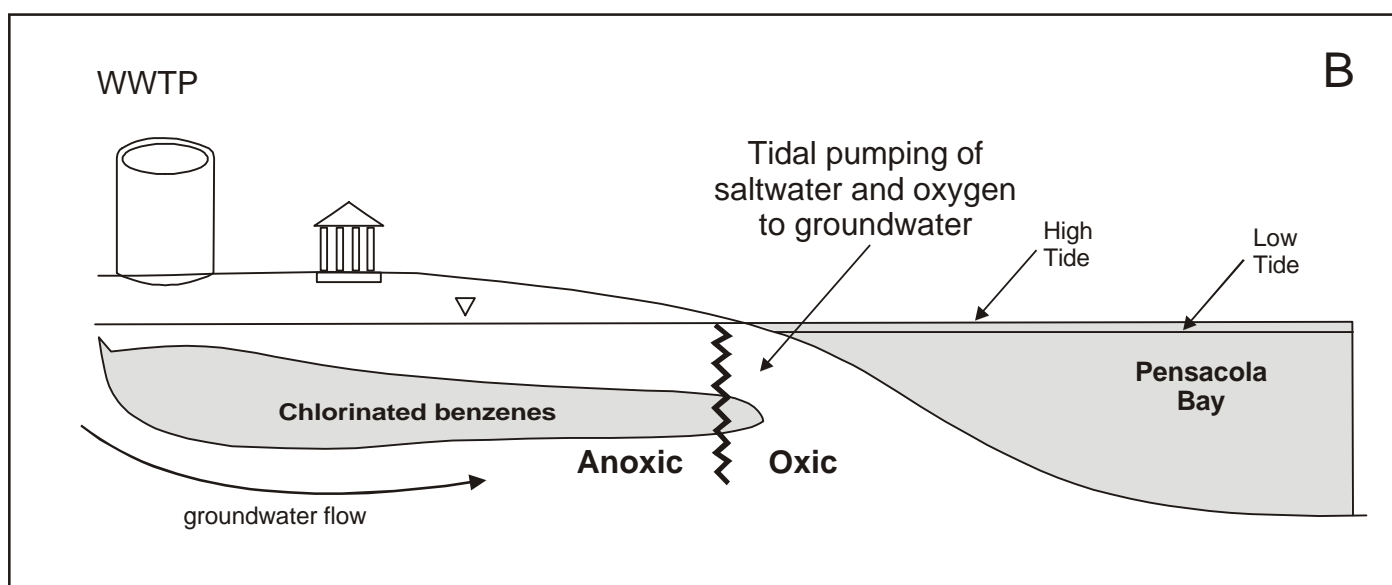
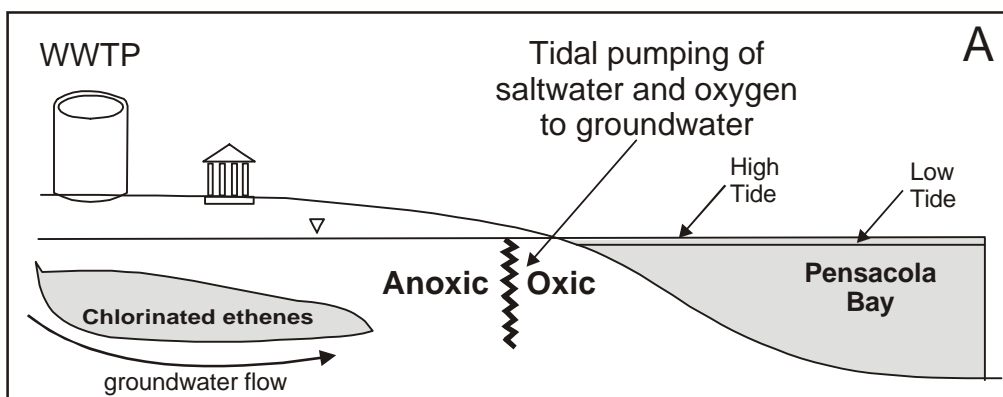


Figure 7. Schematic diagram showing (A) observed anoxic degradation of chlorinated ethenes in groundwater and (B) inferred oxic degradation of chlorinated benzenes where oxygen is delivered to groundwater by tidal pumping

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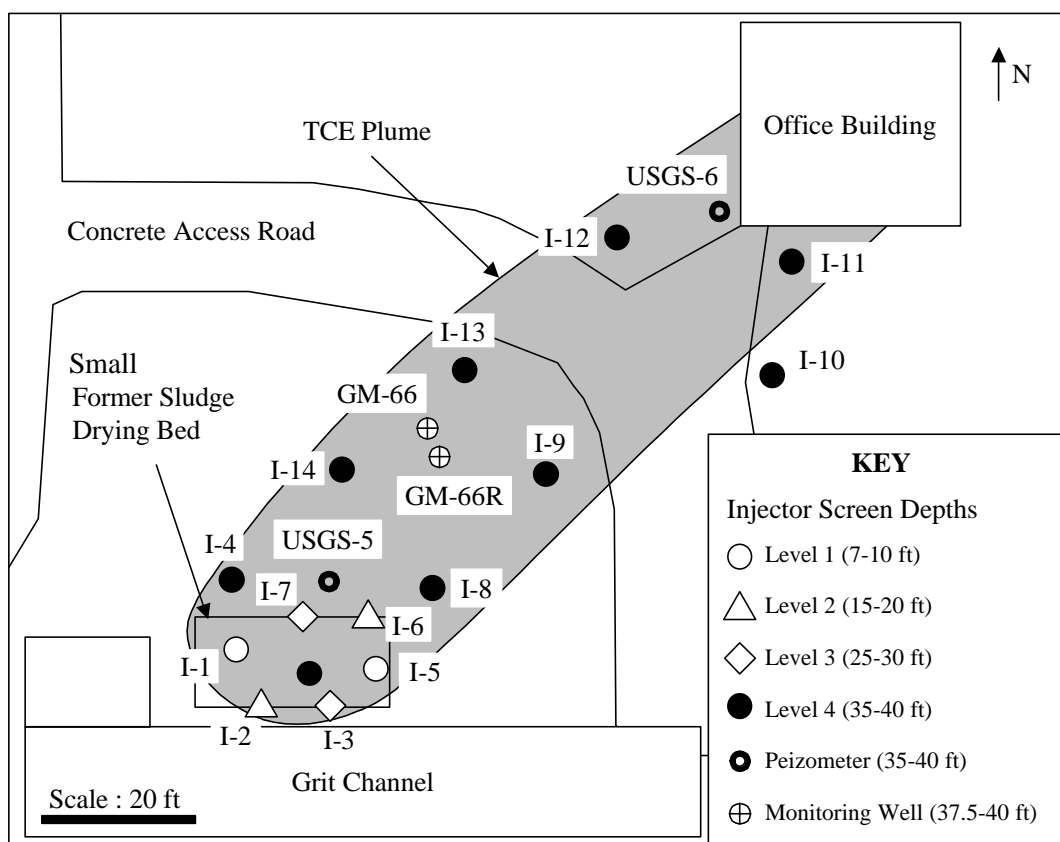


Figure 8. Location of injection wells and interpreted plume area

Figure 9. Overall Trichloroethene Results from Chemical Oxidation Treatments

